U. S. NAVAL SUBMARINE MEDICAL CENTER

Submarine Base, Groton, Conn.

REPORT NUMBER 573

THE EFFECT ON PULMONARY FUNCTIONS OF RAPID COMPRESSION IN SATURATION-EXCURSION DIVES TO 1000 FEET

by

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and

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Bureau of Medicine and Surgery, Navy Department
Research Work Unit MR005.04-0063.04

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15 March 1969

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SUBMARINE MEDICAL RESEARCH LABORATORY
NAVAL SUBMARINE MEDICAL CENTER REPORT NO. 573

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SUMMARY PAGE

THE PROBLEM

To determine effects of helium-oxygen saturation-excursion diving to depths down to 1,000 feet on pulmonary mechanics, using rapid compression schedules.

FINDINGS

Four subjects were studied; two were saturated at 600 feet with excursion dives to 800 feet, and two made excursion dives to 1,000 feet from a saturation depth of 800 feet. Maximum Expiratory and Inspiratory Flow Rates increased 44% and 23%, respectively, during 35-36 hour saturation periods. Vital Capacity decreased during compression and decompression periods, and showed a consistent trend to increase from the beginning to the end of the saturation period. There was evidence of acute air trapping in flow volume loops. Airway collapse during rapid compression and reopening during the subsequent saturation period is proposed as the most likely explanation of observed changes.

APPLICATIONS

Findings indicate the need to be cautious with rapid compression schedules to cause less impairment in pulmonary mechanics. The remarkable recovery of maximal respiratory flow rates during saturation indicates that predictions of respiratory depth limits cannot be based on brief exposures to high pressure.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MR005.04-0063—Excursion Dives from the Gas-Saturated State at Depth. The present report is No. 4 on this Work Unit. It was approved for publication on 15 March 1969, and designated as SubMedResLab Report No. 573.

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ABSTRACT

Four subjects were rapidly compressed at a rate of 2 — 3.5 feet per minute to 600 and 800-foot depths. They remained at saturation depths for 35 and 36 hours and carried out excursion dives lasting three hours to 800 and 1,000 feet, respectively. Maximal Expiratory Flow Rate (MEFR) and Maximal Inspiratory Flow Rate (MIFR) measured with a Wedge spirometer at 200-foot increments during rapid compression showed a linear decrease with the increase in pressure. During the 35-36 hour saturation period, MEFR increased 33-55% ; and MIFR rose 16-30% from the initial values obtained at saturation depths. The recovery of MEFR was not limited to peak flow rates, but also pronounced at the MEFR measured at 50% of vital capacity, indicating that the recovery was independent of muscular effort. Airway collapse during rapid compression and reopening during the subsequent saturation period is proposed as the most likely explanation for the observed changes. Vital capacity decreased during the compression and decompression period and showed a tendency to increase during the saturation period. Evidence of air-trapping was seen in flow-volume loops measured at depth.

THE EFFECT ON PULMONARY FUNCTIONS OF RAPID COMPRESSION IN SATURATION-EXCURSION DIVES TO 1000 FEET

INTRODUCTION

The limits of capacity to work under high pressure are mainly determined by the limits of the respiratory system. Predictions of these limits have been based in the past on the effects of short term exposures to high pressures on respiratory functions such as maximum voluntary ventilation (6). Very few studies have been reported on the effects of prolonged exposure to high pressures on pulmonary functions (1, 5, 7). This report is concerned with the effects of saturation-excursion dives to 800 and 1000 feet following a rapid compression at rates of 2 and 3.5 feet/minute, respectively. The results demonstrate remarkable adjustments of maximal respiratory flow rates during the saturation period; this finding indicates that limits of capacity of the respiratory system under extreme pressures cannot be predicted on the basis of brief exposures to high pressure.

MATERIAL AND METHODS

These studies were a joint effort between International Underwater Contractors, Inc. (I.U.C.) of College Point, New York; Air Reduction Company's Advanced Engineering Laboratories (Airco) at Murray Hill, New Jersey; and the Naval Submarine Medical Center (NSMC), Groton, Connecticut.

The decompression schedules were developed by Mr. Andre Galerne, of I. U. C. The oxygen tensions varied from 300 to 450 millimeters of mercury (mm Hg) during the compression, saturation, and excursion periods. During decompression a special gas mixture (3.5 atmospheres of nitrogen = 2,660 mm Hg and 1.4 atmospheres of oxygen = 1,064 mm Hg), with helium comprising the balance, was breathed through a respiratory mask for 10 minutes at every 100-foot level from 600 feet to 200 feet. However, during the last 50 feet of decompression 100% oxygen was inhaled by mask, alternating with 21% O_2 every 20 minutes (P_{O_2} = 760 — 1912 mm Hg).

Dive Summary

This study consisted of two deep saturation-excursion dives in a pressure chamber, utilizing a breathing mixture which consisted primarily of helium and oxygen (HeO_2). There was a small percentage of nitrogen present; this nitrogen was present in the chamber air prior to compression. The first dive involved saturation at 600 feet and excursions to 800 feet by both subjects; two subjects were compressed at a rate of 2 feet/min. They spent a total time of 7 days under pressure. During the second dive the compression rate was 3.5 feet/min. Following saturation at 800 feet an excursion dive to 1,050 feet for 30 minutes was made by subject DF, and an excursion dive to 1,112 feet for 5 minutes by subject CD. Later, both divers spent two and three-quarter hours at 1,000 feet; total time under pressure was 13 days. The life support system was developed by Airco Advanced Engineering Laboratory (4); it provided an accurate environmental control. The ambient carbon dioxide partial pressure was kept under two millimeters of mercury at all times during the dives.

A case of decompression sickness (subject DF) on March 18 resulted in the decision to repressurize; the two divers were at a depth of 20 feet; repressurization was stopped at 525 feet.

Pulmonary Function Tests

Lung volumes and flow rates were determined by the maximal inspiratory-expiratory velocity-volume technique. A Wedge spirometer (Model 370 by Med-Science Electronics), a Tektronic type 502A Dual-Beam Oscilloscope, and a Tektronic Oscilloscope Camera Model C-12 with a Polaroid film holder were utilized. The bellows component of the spirometer was placed inside the pressure cham-

ber. The six-wire shielded cable, used to connect the bellows to the power supply-amplifier unit, was cut and modified to allow the electrical signal to pass through the chamber walls. The power supply-amplifier unit, the oscilloscope, and the camera were outside the chamber. This type of spirometer, consisting of a bellows and two linear core transducers (one for volume signal, one for flow signal), is ideally suited for high pressure work since its electrical calibration signal is independent of the density and viscosity of the gas being utilized. Instructions were given to the subject by use of an intercom.

Vital capacity, tidal volume, inspiratory capacity, expiratory reserve volume, maximal expiratory flow rate (MEFR) and maximal inspiratory flow rate (MIFR) were calculated from the protograph.

Subjects were trained before experiments commenced. The effort-dependent characteristics of these tests were explained and the importance of a maximal effort was stressed. The flow-volume loops were run in duplicate. If one of the two loops appeared much smaller in terms of flow or volume by a quick visual inspection, it was discarded and a third determination made. Since these tests are effort dependent, we made an arbitrary rule of using the larger of the two vital capacity values; the inspiratory capacity and expiratory reserve volume data were taken from this same photograph. The larger of the two MEFR and MIFR values was chosen, regardless of which determination it occurred in. Tidal volume data was calculated but is not presented since it was highly variable.

Control values were obtained while breathing air at one atmosphere. It was felt that this makes it easier to compare the impairment of breathing under pressure with that under normal conditions; i.e., air, not a mixture of 80% helium and 20% oxygen is what one normally breathes at the surface. During the pressurization the percentage of helium increased, and the percentage of oxygen was decreased. For example, at 200 feet He=80% and O_2=7.5%; at 1,000 feet He=98.5% and O_2=1.2%. The relative gas density was calculated for each of the depths or pressures in terms of moist air at 760 millimeters of mercury and 30 degrees Centigrade (the average chamber and, consequently, spirometer temperature).

RESULTS

The time course of changes in the lung functions studied in the two saturation-excursion experiments are depicted in the first two figures. Figure 1 shows a decrease in MEFR and MIFR with the increase in pressure from 0-600 feet; the partial recovery of these parameters during the time of saturation at 600 feet is seen. Vital capacity was decreased during the entire period of compression in both subjects. None of these values returned to control levels in either diver immediately after decompression to the surface. Subject BW was re-examined approximately one month later and had regained the loss of vital capacity.

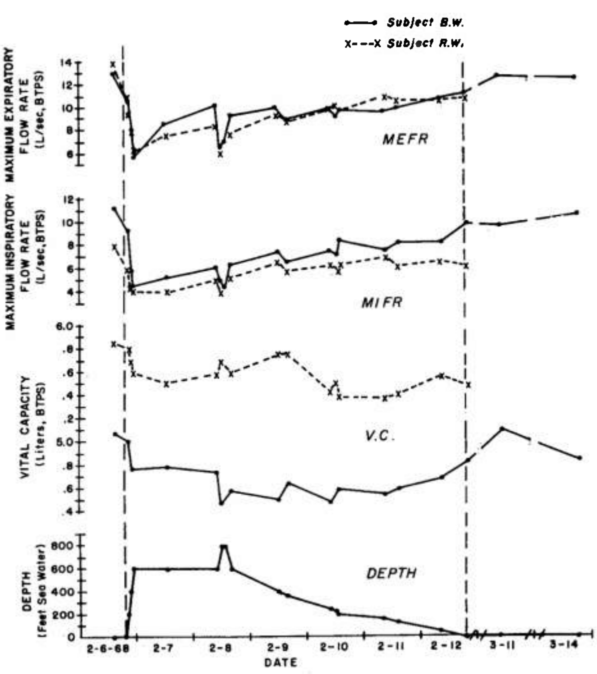

Fig. 1. **Time Course of MEFR, MIFR, VC and Dive Profile (depth) for 600-foot Saturation with Excursions to 800 Feet.**

Figure 2 shows the same data for subjects DF and CD. The MEFR and MIFR follow similar patterns as with subjects BW and RW. Vital capacity is also reduced during pressurization and tends to increase again during decompression.

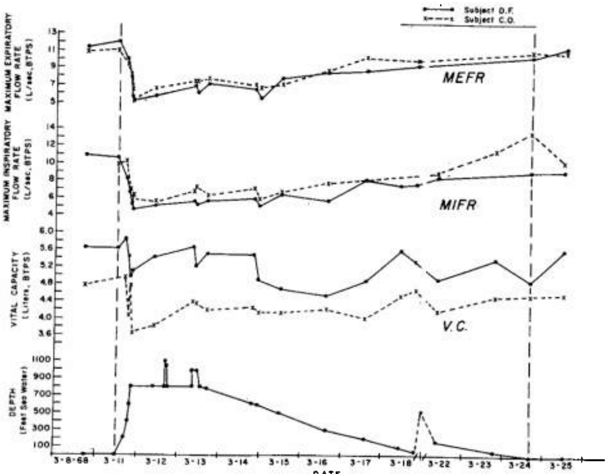

Fig. 2. **Time Course of MEFR, MIFR, VC and Dive Profile (depth) for 800-foot Saturation with Excursions to 1050 and 1112 Feet.**

In Figures 3 and 4, data on MEFR and MIFR are plotted against depth in feet of sea water and corresponding relative gas density. During acute compression MIFR decreased approximately linearly with increasing pressure and density. Following a 36-hour saturation period at both 600 and 800 feet, MIFR increases again. A similar increase is noted 24 hours after return to the surface.

Figure 4 demonstrates how pressure affects the peak expiratory flow rates and the flow rates at 50% and 15% vital capacity. MEFR at nearly full vital capacity decreases with increasing pressure to about one-half of the control value at 600 to 800 feet. A partial recovery after saturation at 600 and 800 feet is shown. The MEFR at 50% of the vital capacity shows a response to pressure very similar to that of the peak expiratory flow rate pattern during the saturation period. The values are about half of those of the peak flow; i.e., 6.67 liters/second for the control and 2.9 liters/second at 800 feet initially.

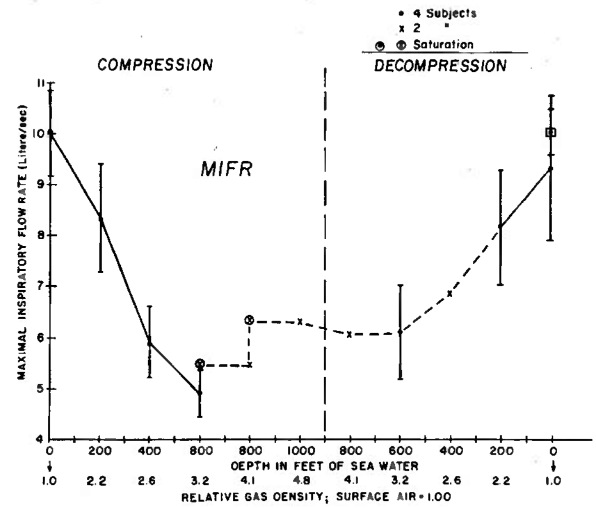

Fig. 3. **Effect of Pressure (equivalent feet of sea water) and Density of Ambient Gas on Maximal Inspiratory Flow Rate during Two Chamber Dives with Two Subjects Each. (Values within O are after Saturation at 600 and 800 feet; the Value within □ Represents One Day Post-Dive Values fir TWo Subjects, and One Month Post-Dive for One Subject. Means and standard error of means are shown.)**

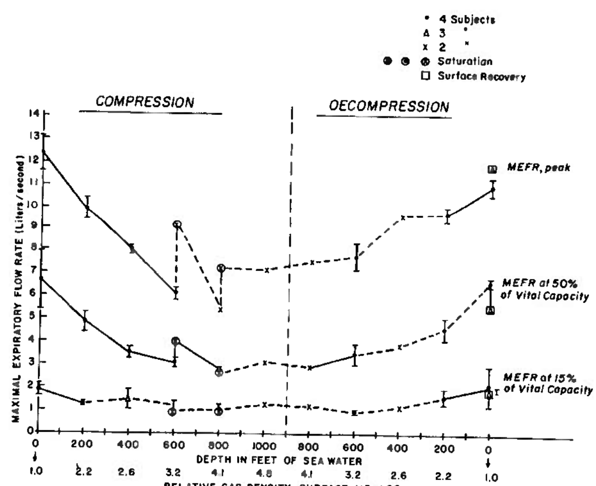

Fig. 4. **Effect of Pressure (equivalent feet of sea water) and Density of Ambient gas on Maximal Expiratory Flow rate at Three Lung Volumes during Two Chamber Dives with Two Subjects Each. (Values within O are after Saturation at 600 and 800 Feet; the value within □ Represents One Day Post-Dive Values for Two Subjects, and one month Post-Dive for One Subject. Means and standard error of means are shown.)**

The MEFR at 15% of vital capacity (i.e., near the residual position) follows somewhat the same pattern, following from a control of 1.8 liters/second to 0.9 liters/second at 600 feet. However, this last curve seems to be less reliable than those at larger lung volumes; some of the points are out of line. This may be due to the difficulty of accurate measurement from the photograph at such low flow rates.

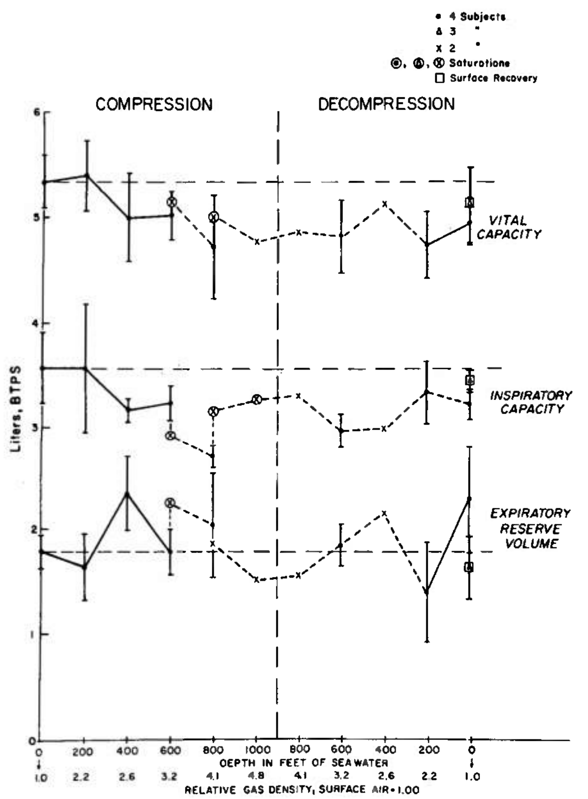

Fig. 5. Effect of Pressure (equivalent feet of sea water) and Density of Ambient Gas on Vital Capacity, Inspiratory Capacity, and Expiratory Reserve Volume.

The astonishing recovery of inspiratory and expiratory flow rates during the saturation periods increases with time as it is shown in Table I and II. The values obtained after 35-36 hours of saturation are larger than those obtained at 12-14 hours.

Figure 5 exhibits all the data on vital capacity, inspiratory capacity and expiratory reserve volume obtained in the four subjects during the saturation-excursion dives plotted against pressure (depth) and relative gas density. Vital capacity decreased during both compression and decompression; differences from controls becoming statistically significant during the decompression period, Table IIIa. Moreover, a steady rise of vital capacity can be noted from the beginning to the end of the 36-hour saturation period, although the differences do not reach statistical significance due to the small number of subjects, Table IIIb. Immediately upon return to the surface, vital capacity was below the control value in all four divers. However, control values were reached in two subjects retested after one day and one subject retested after one month.

The inspiratory capacity shows a similar pattern, but reaches control values on return to the surface. Expiratory reserve volume shows no consistent change during the saturation-excursion dives.

TABLE I. IMPROVEMENT OF MAXIMUM EXPIRATORY AND INSPIRATORY FLOW RATES AFTER SATURATION DURING DIVING TO 600 FEET

	MEFR (L/sec) Subject			MIFR (L/sec) Subject		
	BW	RW	Mean	BW	RW	Mean
Surface control	12.96	13.90	13.43	11.23	7.90	9.57
600 feet, 0 hours	5.75	6.24	6.00	4.42	3.97	4.20
600 feet, 14 hours saturation	8.57	7.46	8.02	5.15	3.84	4.50
△ 0 hours, L/sec	2.82	1.22	2.02	0.73	—0.13	.30
% change from 0 hours	49%	20%	**35%**	17%	—3%	**7%**
600 feet, 35 hours saturation	10.12	8.27	9.20	5.97	4.95	5.46
△ 0 hours, L/sec	4.37	2.03	3.20	1.55	0.98	1.26
% change from 0 hours	76%	33%	**55%**	35%	25%	**30%**

TABLE II. IMPROVEMENT OF MAXIMUM EXPIRATORY AND INSPIRATORY FLOW RATES AFTER SATURATION DURING DIVING TO 800 FEET

	MEFR (L/sec) Subject			MIFR (L/sec) Subject		
	DF	CD	Mean	DF	CD	Mean
Surface control	11.50	11.07	11.29	10.65	9.97	10.31
800 feet, 0 hours	5.38	5.46	5.42	4.69	6.25	5.47
800 feet, 12 hours saturation	5.90	6.77	6.34	5.20	5.55	5.38
△ 0 hours, L/sec	0.52	1.31	0.92	0.51	—0.70	—0.09
% change from 0 hours	10%	24%	17%	11%	—11%	0%
800 feet, 36 hours saturation	6.99	7.44	7.22	5.67	6.92	6.30
△ 0 hours, L/sec	1.61	1.98	1.80	0.98	0.67	0.83
% change from 0 hours	30%	36%	33%	21%	11%	16%

TABLE III-a. EFFECT OF SATURATION EXCURSION DIVES TO 800 FEET ON VITAL CAPACITY+

	Pre-dive	Compression				Decompression		Post-dive	
Vital Capacity L/BTPS	Surface Control	200	400	600	800	600	200	Initial	1-30 days following dive
Mean	5.35	5.40	5.00	5.01	4.72	4.81*	4.73*	4.95	5.11
S.E.M.	.27	.33	.42	.23	.44	.35	.32	.22	.37
N	4	4	4	4	4	4	4	4	3
Percent of surface control	100.	101	93.1	93.8	87.7	89.9	88.4	92.5	101**
(5.35 equals 100%)									

+ Since only 2 values were obtained at 1000 feet depth on 2 subjects, they were not included in this table.

* Data obtained at individual depth level show statistically significant differences from control values at the 5% level and better.

** Based on mean control value for same three divers of 5.07 liters.

Figure 6 exhibits graphic evidence of acute air trapping during the forced expiratory volume determination in subject BW. The expiratory loops do not close in the photographs taken at depth. This occurred occasionally in all four subjects; it was most frequent in subject BW where it was evident in the majority of the photographs taken at depths over 400 feet. This sign of air trapping is seen at 400 and 200 feet during decompression, and has disappeared on return to the surface.

TABLE III-b. CHANGES IN VITAL CAPACITY DURING SATURATION PERIODS OF 12-14 HOURS AND 35-36 HOURS AT 600 AND 800 FEET SATURATION PERIOD

	Saturation period		
	0 hours	**12-14 hours**	**35-36 hours**
Mean, L/BTPS	4.77	4.88	5.08
S.E.M.	.48	.45	.36
N	4	4	4
Percent of surface control	89	91	95

(5.35 equals 100%)

DISCUSSION

Maximal inspiratory and expiratory flow rates decreased progressively with increasing gas density. The values obtained are in agreement with those reported in the literature.[5,7,8] Extending previous findings on air breathing under pressure,[2] a significant recovery of maximal inspiratory and expiratory flow rates during saturation at depth was demonstrated. Since the gas density causing the increased airway resistance remains during the saturation period, other factors must have contributed to the increase in maximal expiratory and inspiratory flow rates during the saturation period.

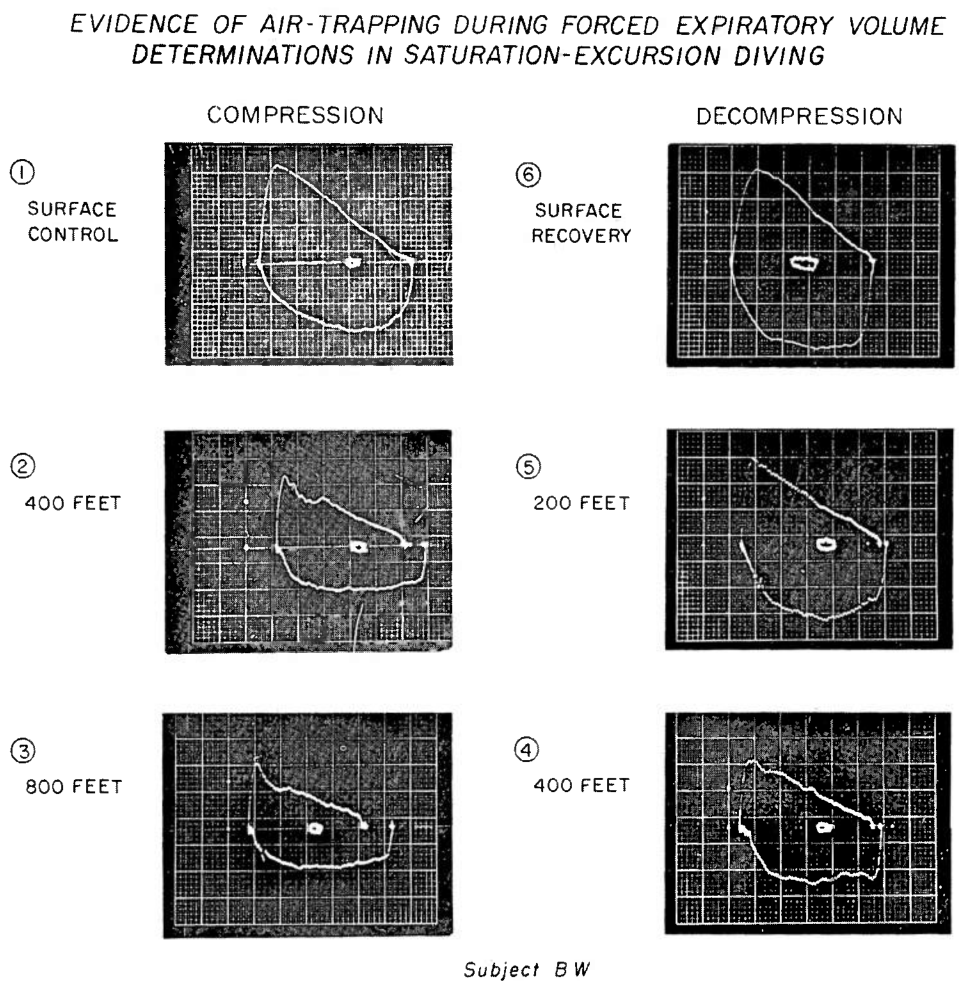

Fig. 6. Evidence of Air Trapping in Flow-Volume Loops at Pressure. (Subject does not close loop, i.e., reach the same residual position during forced vital capacity maneuvers that had been reached previously during slow expiratory effort.)

It is the authors opinion that the four subjects gave a maximal effort in all but a few instances by subject CD. These few values were discarded from the final graphs and tables. It might be argued that the improvement during the saturation period was simply a training effect. We tend to discount this as we feel the subjects were well trained before experiments started. Also, the order of the experiments in our previous paper (2) would contradict a training effect. In that study, saturation at 35 feet while breathing air and excursions to depths of 100 to 165 feet on air were made. There was also an improvement in MIFR and MEFR during saturation. At a later time when the subjects should be even better trained, if they had not previously reached a training plateau, they were taken to the previous excursion depth for each individual diver (range 100-165 feet) directly from the surface. The impairment of MIFR and MEFR was greater than the earlier values at the same depth which followed the 35-foot saturation.

It has been suggested that, at pressures corresponding to a relative gas density of 5, the respiratory muscles can be more effective than at normal atmosphere pressures[8] and one could consider an adaptation of the respiratory muscles as the cause of the flow rate recovery during the saturation period. However, the recovery of maximal expiratory flow rates is not limited to peak flow rates which are effort-dependent but is also pronounced at MEFR at 50% vital capacity which is independent of effort.[9]

Since there were no adaptive changes in the maximal expiratory flow rate at low lung volumes (15% vital capacity) it must be concluded that the recovery of flow rate at vital capacity and at 50% vital capacity are related to changes in conductance of the medium and larger airways.

The air flow in the small airways and alveoli is apparently not affected in saturation-excursion diving. The principal determinant of the air flow in the small airways and alveoli is, according to Mead, et al,[9] the elastic recoil. Recent evidence showing that dynamic pulmonary compliance did not change during and after two weeks of breathing a helium-oxygen atmosphere up to 19.2 atmospheres,[1] corresponding to 600-foot depth under conditions similar to our experiments, supports the notion that the elastic properties of the lungs were not altered.

In our experiments, vital capacity tended to decrease during the compression period from the 400-foot level on, without reaching statistical significance. However, the reduction in vital capacity became statistically significant during the decompression period. This is in contrast to the small increases in vital capacity observed in similar saturation diving experiments carried out at the Experimental Diving Unit (EDU), in Washington. The difference might be explained by the much slower compression schedule used in the EDU experiment, which was 0.66 feet/min. Moreover, the consistent increase of vital capacity from the beginning to the end of the saturation period found in our experiments suggests that air had been trapped in collapsed airways during the rapid compression and was slowly released with the opening of the airways during the saturation period. The airway collapse theory has been previously discussed by Maio and Farhi,[8] and A. DuBois.[3] There is a higher pressure gradient between the alveolus-bronchus under the influence of high velocity as the air increases in density. The pleural pressure acting on the outside of the bronchus tends to collapse it, a situation which results in air trapping.

The reopening of the collapsed airways during the saturation period would also satisfactorily explain the remarkable recovery of the maximal expiratory and inspiratory flow rates. The evidence of air trapping shown in the flow-volume loop tracings in Figures 6, which is most pronounced during the compression, further supports the notion of the airway collapse. In some of the flow-volume loops determined at depth there was a failure to close. This is, we believe, the same phenomenon that occurs in airway obstruction, in which the slow vital capacity is greater than the forced vital capacity. The higher intepleural pressure may cause airway

collapse in these cases. In the procedure used, we had the subject exhale to the residual position following normal tidal breathing; this was done at a comfortable rate. A maximal inspiration followed, then the forced vital capacity (FVC) maneuver was performed. The vital capacity measurement was made from the point representing the residual position after a slow expiration to the point reached at the end of the maximal inspiration. In the case of the unclosed loops, this same residual position was not reached again following the FVC maneuver, The discrepancy between the two residual positions may be considered as air temporarily "trapped" by the FVC maneuver, and is in addition to the loss of vital capacity shown in the tables and graphs. During the decompression phase repeated 10-minute breathing of gas mixtures with a higher nitrogen and oxygen partial pressure ($Po_2 =$ 1000 mm Hg) might have produced some alterations in the ventilation-perfusion relationships in the lungs. This is indicated in the findings obtained by radiographic scanning of the lungs. These studies were performed by Dr. A. D. Crosett, Jr., Overlook Hospital, Summit, N. J., who kindly made his results available to us. The lung scans were carried out, using a dose of 290 microcuries of I^{-131} (radioactive isotope of iodine) labelled human serum albumin three hours following emergence from the pressure chamber and one week later in two divers participating in the 800-foot saturation-excursion dives and prior to and after the dive in the two divers involved in the 1000-foot saturation-excursion dive.

In all cases, a slight increase in peripheral perfusion of the lungs was noted immediately after the dive. The results of these investigations are in line with our observations that vital capacity was below control values on reaching the surface and increased to initial values during the recovery period following the dive.

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13. ABSTRACT

Four subjects were rapidly compressed at a rate of 2 - 3.5 feet per minute to 600 and 800-foot depths. They remained at saturation depths for 35 and 36 hours and carried out excursion dives lasting three hours to 800 and 1,000 feet, respectively. Maximal Expiratory Flow Rate (MEFR) and Maximal Inspiratory Flow Rate (MIFR) measured with a Wedge spirometer at 200-foot increments during rapid compression showed a linear decrease with the increase in pressure. During the 35-36 hour saturation period, MEFR increased 33-35%; and MIFR rose 16-30% from the initial values obtained at saturation depths. The recovery of MEFR was not limited to peak flow rates, but also pronounced at the MEFR measured at 50% of vital capacity, indicating that the recovery was independent of musclar effort. Airway collapse during rapid compression and reopening during the subsequent saturation period is proposed as the most likely explanation for the observed changes. Vital capacity decreased during the compression and decompression period and showed a tendency to increase during the saturation period. Evidence of air-trapping was seen in flow-volume loops measured at depth.

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